

MEASURING THE HIGGS YUKAWA COUPLINGS AT A NEXT LINEAR COLLIDER

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We investigate the inclusive production of a Higgs boson with a pair of heavy quarks ($t\bar{t}$ or $b\bar{b}$), in e^+e^- collisions at high energies, $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1$ TeV. We consider both the Standard Model and the supersymmetric case. In both cases $O(\alpha_s)$ QCD corrections are included. The associated production of a Higgs boson with a $t\bar{t}$ pair is extremely sensitive to the top-Higgs Yukawa coupling and may allow the precision measurement of this coupling. In some regions of the supersymmetric parameter space the associated production of a Higgs boson with a $b\bar{b}$ pair receives large resonant contributions and can have a significant rate.

1 Introduction

The origin and hierarchy of particle masses remains one of the most tantalizing problems in contemporary particle physics. The untangling of the electroweak symmetry breaking is among the very important and challenging goals of the present and next generation of colliders. In this context the search for the Higgs boson and the study of its couplings to gauge bosons and fermions are crucial.

Recent bounds from LEP2 have pushed the Higgs mass up to: $M_\phi > 95.2$ GeV (Standard Model, $\phi = H_{SM}$)¹ and $M_\phi > 81$ GeV (minimal Supersymmetry, $\phi = h^0, A^0, \tan\beta > 0.5$)². At the same time, there are strong theoretical reasons to believe that, if our understanding of the electroweak symmetry breaking is correct, a light mass Higgs boson ought to exist. This is definitely possible in the Standard Model and mandatory in the minimal version of Supersymmetry, where the upper bound on the mass of the light Higgs scalar is around 130 GeV. We therefore focus on the possibility that a so called *intermediate mass Higgs* exists, with a mass in the range between 100-130 GeV.

If such Higgs boson exists, chances are that it will be discovered maybe at the present (LEP2) and for sure at the future generation of colliders (Tevatron RunII or LHC). A high energy Next Linear Collinear (NLC) would then be the ideal environment for precision studies. In this context the $e^+e^- \rightarrow t\bar{t}\phi$ and $e^+e^- \rightarrow b\bar{b}\phi$ production modes can offer the unique possibility of a direct measurement of the top ($g_{t\bar{t}\phi}$) and bottom ($g_{b\bar{b}\phi}$) Yukawa couplings, both at

$\sqrt{s}=500$ GeV and at $\sqrt{s}=1$ TeV. The production rates are small (of the order of a few femtobarns), but the signatures can be quite spectacular, in particular for the $t\bar{t}\phi$ case.

We have studied the inclusive associated production of both $t\bar{t}\phi$ and $b\bar{b}\phi$ at high energy e^+e^- colliders ($\sqrt{s}=500$ GeV and $\sqrt{s}=1$ TeV), including $O(\alpha_s)$ QCD corrections^{3,4}. QCD corrections to $e^+e^- \rightarrow t\bar{t}H_{SM}$ have also been computed in reference⁵. Both in the Standard Model and in Supersymmetry, the $e^+e^- \rightarrow t\bar{t}\phi$ production mode turns out to be extremely sensitive to the top Yukawa coupling $g_{t\bar{t}\phi}$, allowing a very precise measurement of the coupling itself. We discuss the $t\bar{t}\phi$ case in Section 2. On the other hand, the $e^+e^- \rightarrow b\bar{b}\phi$ production mode has a negligible rate in the Standard Model, but gets enhanced by resonance effects in some regions of the supersymmetric parameter space. Therefore it can provide evidence of non standard physics. We discuss the $b\bar{b}\phi$ case in Section 3. Section 4 contains our conclusions.

2 Associated production of a Higgs boson with a $t\bar{t}$ pair

2.1 Standard Model

In the Standard model ($\phi=H_{SM}$), the $t\bar{t}H_{SM}$ final state can be produced both when the Higgs is radiated from a final state top quark and when it is radiated by the intermediate Z boson^{3,5}. In general a measurement of the inclusive cross section would provide some mixed determination of both $g_{t\bar{t}H}$ and g_{ZZH} couplings. However, a more careful analysis of the analytical properties of the cross section shows that the ZZH_{SM} contribution is almost irrelevant and most of the cross sections come from the *abelian* diagrams, i.e. the diagrams where the Higgs is radiated from the final state top quarks. Even more, they are indeed the diagrams with a photon exchange that dominate, providing almost 98% of the tree level cross section (σ_0) at $\sqrt{s}=500$ GeV and almost 90% at $\sqrt{s}=1$ TeV⁶, as illustrated in Fig. 1 (left plot).

We have computed the inclusive cross section including the complete set of $O(\alpha_s)$ QCD corrections³ (σ_1). Since the photon contribution is dominant both at $\sqrt{s}=500$ GeV and at $\sqrt{s}=1$ TeV, we did not include the Z diagrams in our calculation. Reference⁵ includes the Z contributions too and gets very similar results.

We take the renormalization scale $\mu = m_t$, the top mass $m_t = 175$ GeV and the strong coupling constant $\alpha_s(m_t^2) = 0.11164$. The uncertainty due to the input parameters is very small, the residual renormalization scale (μ) dependence is about 10% and, contrary to hadronic processes, we expect the $O(\alpha_s^2)$ QCD corrections to be small. The results are illustrated in Fig. 1 (right

plot). The effects of QCD corrections are large and positive at $\sqrt{s}=500$ GeV,

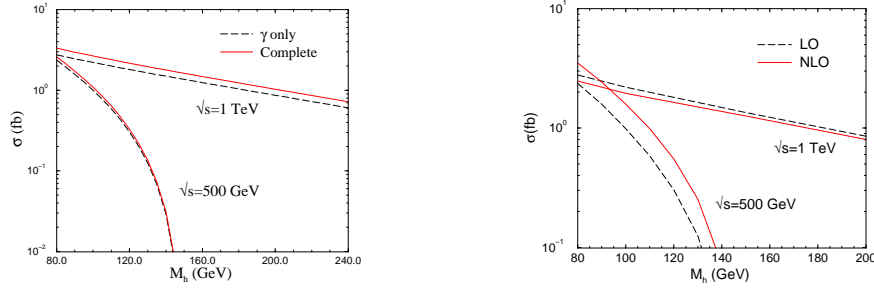


Figure 1: *Left plot*: lowest order cross section for $e^+e^- \rightarrow t\bar{t}h$: the photon only contribution is compared to the total cross section. The curve labelled *complete* includes both γ and Z exchange, along with bremsstrahlung from the Z boson. *Right plot*: the $O(\alpha_s)$ QCD cross section is compared to the lowest order cross section. In both cases, curves are shown for both $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1$ TeV.

because of resonance effects, and small and negative at $\sqrt{s} = 1$ TeV. If we define the K -factor for this production mode to be

$$K(\mu) = \frac{\sigma_1}{\sigma_0} \quad \text{then} \quad \begin{cases} K(\sqrt{s} = m_t) \simeq 1.4 - 2.4 & \text{for } \sqrt{s} = 500 \text{ GeV} , \\ K(\sqrt{s} = m_t) \simeq 0.8 - 0.9 & \text{for } \sqrt{s} = 1 \text{ TeV} . \end{cases} \quad (1)$$

It is interesting to note that the result for $\sqrt{s} = 1$ TeV agrees with the estimate obtained in the Effective Higgs Approximation⁷, showing the validity of this approximation for center of mass energies around or above $\sqrt{s} = 1$ TeV.

It is clear that the measurement of the $g_{t\bar{t}H}$ coupling will be difficult at an NLC with $\sqrt{s} = 500$, but it can be achieved with higher center of mass energies. A first study of the background⁸ confirmed that the $e^+e^- \rightarrow t\bar{t}H_{SM}$ signal has a very distinctive signature ($W^+W^-b\bar{b}b\bar{b}$) and offers many handles to reduce both the electroweak ($e^+e^- \rightarrow t\bar{t}Z \rightarrow W^+W^-b\bar{b}b\bar{b}$) and the QCD ($e^+e^- \rightarrow t\bar{t}g \rightarrow W^+W^-b\bar{b}b\bar{b}$) backgrounds. Stimulated by discussions during this series of NLC workshops, real simulation analyses have been recently performed^{9,10}. They agree on the fact that for center of mass energies of the order of $\sqrt{s} = 1$ TeV or higher, a precision of about 10% can be reached on $g_{t\bar{t}H}$.

2.2 Supersymmetry

In the minimal supersymmetric model we have to consider the associated production of a $t\bar{t}$ pair with both the two scalar (h^0 , the lighter one, and H^0 ,

the heavier one) and the pseudoscalar (A^0) Higgses. The processes $e^+e^- \rightarrow t\bar{t}H^+$, $t\bar{t}H^-$ are only interesting in the small mass region where H^\pm cannot decay to t nor t decay to H^\pm and we will not consider them further⁶.

The masses and couplings of h^0 , H^0 and A^0 varies over the minimal supersymmetry parameter space, which we describe using the canonical $(M_A, \tan\beta)$ parametrization. In the *intermediate mass region*, and varying $\tan\beta$ between 2.5 and 40, we find that the cross section for $e^+e^- \rightarrow t\bar{t}h_i^0$ (for $h_i^0 = h^0, H^0$) at $\sqrt{s}=500$ GeV, is almost always larger than 0.75 fb, and grows for $\sqrt{s}=1$ TeV. On the other hand, the cross section for $e^+e^- \rightarrow t\bar{t}A^0$ is always very small (e.g., less than 10^{-2} fb for $\sqrt{s}=500$ GeV).

The inclusive cross section now contains a purely supersymmetric contribution given by $e^+e^- \rightarrow Z^* \rightarrow A^0 h_i^0 \rightarrow b\bar{b}h_i^0$, due to the $ZA^0 h_i^0$ couplings⁴. This new term could spoil the sensitivity of $t\bar{t}h_i^0$ production to the corresponding Yukawa couplings. Remarkably enough this does not happen for the top quark case, and the inclusive cross section still consists almost entirely of those diagrams in which the Higgs is radiated from the top quark. Therefore, the precision reach estimated for the Standard Model case still holds for the supersymmetric case. Moreover, we can compute the $O(\alpha_s)$ cross sections by simply multiplying the tree level supersymmetric results^{6,4} by the K -factors calculated in the Standard Model case. As an example, the values of $\sigma(e^+e^- \rightarrow t\bar{t}h_i^0)$ obtained for the $\sqrt{s}=1$ TeV, can be read from Fig. 2.

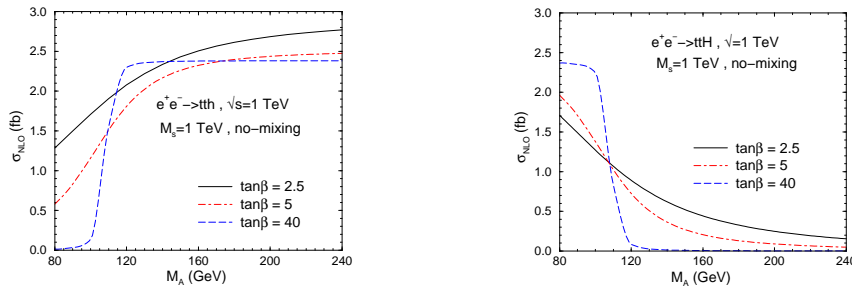


Figure 2: Next-to-leading order result for $e^+e^- \rightarrow t\bar{t}h^0$ (left plot) and $e^+e^- \rightarrow t\bar{t}H^0$ (right plot), at $\sqrt{s}=1$ TeV using $K=0.94$. The squarks are taken to have a common mass, $M_S=500$ GeV, and the scalar mixing is neglected.

3 Associated production of a Higgs boson with a $b\bar{b}$ pair

In the Standard Model, the $e^+e^- \rightarrow b\bar{b}H_{SM}$ production cross section is small and not sensitive to the $g_{b\bar{b}H}$ coupling alone. Contrary to what we have seen

in Section 2.1 for the $t\bar{t}H_{SM}$ case, the $b\bar{b}H_{SM}$ production mode receives very important contributions from $e^+e^- \rightarrow Z^*H_{SM} \rightarrow b\bar{b}H_{SM}$ and the inclusive cross section measurement is therefore sensitive to a mixture of both $g_{b\bar{b}H}$ and g_{ZZH} couplings.

The supersymmetric scenario is however much more interesting since having more Higgs bosons ($\phi = h^0, H^0, A^0, H^\pm$) allows more ways to pin down the fermion-Higgs Yukawa couplings. Moreover in some regions of the supersymmetric parameter space, as for large $\tan\beta$, some of the $b\bar{b}\phi$ couplings can be very enhanced and the $e^+e^- \rightarrow b\bar{b}\phi$ cross sections can be substantially larger than in the Standard Model.

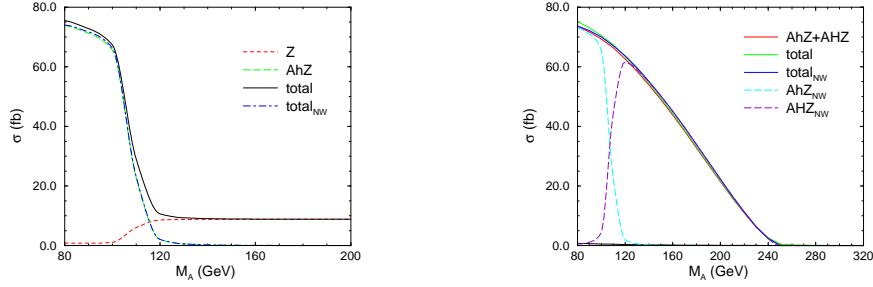


Figure 3: Contributions to $e^+e^- \rightarrow b\bar{b}h^0$ (left plot) and $e^+e^- \rightarrow b\bar{b}A^0$ (right plot) at $\sqrt{s}=500$ GeV, for $\tan\beta=40$. The curve labelled ‘NW’ is the narrow width approximation of the cross section and it includes QCD corrections in the resonance region. The squarks are assumed to have a common mass, $M_S=500$ GeV, and the scalar mixing is neglected.

Another interesting fact is that large resonant contributions affect the genuinely supersymmetric production mode $e^+e^- \rightarrow h_i^0 A^0 \rightarrow (h_i^0, A^0)b\bar{b}$, when $M_A \simeq M_{h_i}$, i.e. for low values of M_A . In the resonant region, the $ZA^0h_i^0$ contribution is of course dominant compared to both top-Higgs and Z-Higgs bremsstrahlungs, and can increase the production rates by more than one order of magnitude. This is true both for the scalars h^0, H^0 and for the pseudoscalar A^0 Higgs boson, and multiple measurements of $g_{bb\phi}g_{ZA^0h_i^0}$ can be obtained. We can work in the narrow width approximation and include $O(\alpha_s)$ QCD corrections by simply taking into account $O(\alpha_s)$ corrections to the width of the resonant Higgs boson. As soon as we move from resonance, this is not true anymore: the Z-Higgs bremsstrahlung contribution becomes important, even dominant, and the inclusion of $O(\alpha_s)$ QCD corrections would require a complete calculation. However, we are only interested in the resonant region, since only here are the rates enhanced.

Examples of $\sigma(e^+e^- \rightarrow b\bar{b}h^0)$ and $\sigma(e^+e^- \rightarrow b\bar{b}A^0)$ are given in Fig. 3,

where the $ZA^0h_i^0$ resonances, the excellence of the narrow width approximation (NW) and some of the previously described characteristics are evident.

4 Conclusions

The associated production of a Higgs boson with a $t\bar{t}$ quark pair may allow the precision measurement of the top Yukawa coupling at a Next Linear Collider. We have calculated the production rate at $O(\alpha_s)$ and analyzed both the Standard Model and the minimal supersymmetric case. In both cases a 10% level precision is reachable, for $\sqrt{s}=1$ TeV or higher. The associated production of a Higgs boson with a $b\bar{b}$ pair, although negligible in the Standard Model, can be very interesting in some regions of the minimal supersymmetry parameter space, due to enhanced couplings and resonant contributions.

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